CHAPTER 2

Basic Concepts

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CHAPTER 2

Basic Concepts

The Ship as a Simple Beam

1 The first user of the beam as a structural analogy for the ship on a wave is lost in antiquity, but it is Attwood and Pengelly (1922) who first illustrate it as a beam with several flanges as in *Figure 2.1* which shows a beam idealisation for vertical plane bending about the neutral axis. This arrangement separates the transverse and longitudinal structure and has been found to be very effective for estimating first order bending response about both short axes, but different simple beam idealisations are required for different load directions. Shear response is strongly influenced by the position of members in the plane of the applied shear load and by the continuity of box sections, and it is therefore usual to ignore shear effects (but not shear loads) in the initial assumptions. In addition it will always be necessary to take great care in judging what structure is effective in the bending direction in question.

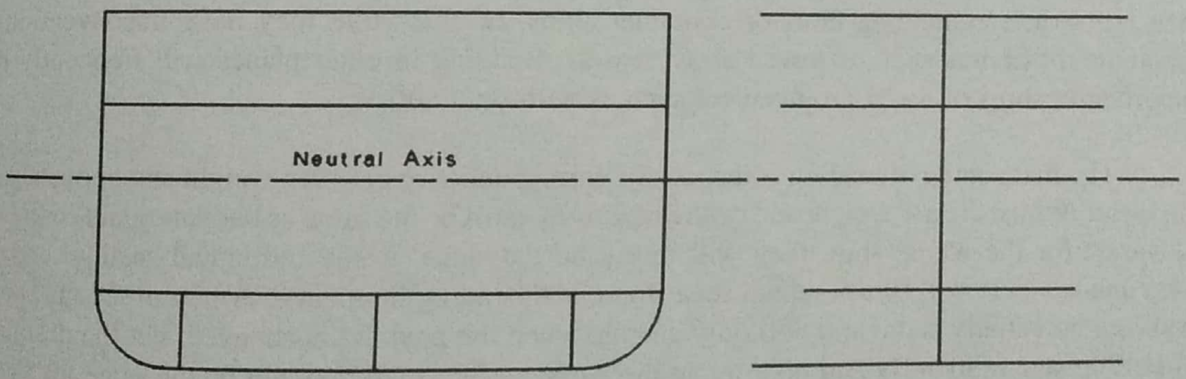

Figure 2.1 The Hull as a Flanged Beam

Effective Structure

2 The effectiveness of any structure in resisting longitudinal bending of the hull depends on its longitudinal extent and on how well it is integrated into the main structure. For example, a superstructure block will always take some bending load as part of the hull, but due to shear effects in the sides of the superstructure plane sections will not remain plane and the rules of simple bending are not strictly valid. This is especially true towards the ends of a block of superstructure, and so it is only appropriate to assume long superstructure blocks to be effective as part of the hull girder. This phenomenon is discussed in more depth in Chapter 8.

3 Similarly, internal structure such as decks, longitudinal bulkheads and deep longitudinal stiffeners such as machinery bearers, are only effective as part of the hull girder at a distance from their ends. Generally if they extend for less than 10% of the ship's length they are not worth considering in hull longitudinal bending calculations. More details on effectiveness of hull structure are given in Chapters 6, 7 and 12.

Torsion

4 Although it is possible to estimate simple torsional effects using the beam analogy, the extent of warping (longitudinal out-of-plane deflections), particular in ships with large deck openings, makes accuracy doubtful. Hull torsional loads are discussed in Chapter 3 and design to resist torsion in Chapter 7. Note that as torsional strength relies in particular on a closed-cell type of structure, continuity and structural effectiveness merit special consideration if torsion is an important aspect of design.

Structural Loading

Longitudinal Loads

5 Ships are subject to longitudinal bending moments and shear forces in both the vertical and horizontal planes, as well as being subject to torsional moments about their longitudinal axis. In most conventional ships it is found that only the bending moments and shear forces in the vertical plane are of significance in design, although torsion may be of importance in ships with open hulls such as landing craft or container ships, or ships that may have unconventional operating constraints such as towed array vessels. Bending in other planes will frequently be important in ships of novel arrangement such as with twin hulls.

6 The first source of loading is the lack of correspondence between weight and buoyancy in still water. Whilst clearly weight and centre of gravity must be the same as buoyancy and centre of buoyancy for the whole ship, they will rarely be the same at any individual section, and in consequence there will be a resultant shear force and bending moment distribution set up. These loads are essentially static and will only change when the payload is changed, but the designer will often have to identify and investigate the worst cases which may not be the same for shear and bending.

7 For monohull vessels the most important longitudinal loads result from wave action. This gives rise to two groups of cyclic loads. The first of these is due to direct wave action when the weight and buoyancy are out of balance along the length and is an extension of the static out-of-balance mentioned above, but compounded by the dynamic effects of pitch and heave. The worst case is usually when the encounter wave length, allowing for speed and heading, is about the same as that of the ship, and the loads can be estimated with adequate accuracy by assuming the ship to be a rigid beam. The second occurs when a dominant wave frequency corresponds to a natural frequency of the hull girder. For most ships this is a rare happening and hull vibration is much more frequently excited by impulsive loading due to wave impact or slamming of the hull onto the water surface. In some ships, especially small fast craft, these slamming loads can be of

overriding importance in the design of the hull girder as discussed by Savitsky (1985) and Heller and Jasper (1961). As the loads are dependent on the flexibility of the hull they can only be calculated using methods of structural dynamics such as proposed by Bishop and Price (1979). Warships may also suffer in service from underwater explosive loading which has the effect of exciting all the lower resonant modes of vibration and potentially with a much greater amplitude than that due to slamming. Static and dynamic longitudinal loading is discussed in detail in Chapters 3 and 4.

Transverse Loads

8 Ships are also subject to transverse loads due to hydrostatic and dynamic pressure, as well as from elements of the ship's equipment and variable load acting in the vertical transverse plane. Some of these loads are truly static; others are a combination of static and cyclically applied loads, such as hydrostatic pressure on the bottom as the ship passes through waves. A few are impulsive, for example the local effect of sea slap and sloshing in tanks. Nevertheless, for practical design purposes it is necessary to treat almost all of them as static because of lack of knowledge of the true load history and application, one particular exception being the pressure variation induced by propellers on the adjacent hull plating. However, when any load source or unusual structural configuration which might lead to dynamic loading is being considered, care must be taken to ensure that the dynamic effects are properly accounted for when proposing load or strength margins.

9 Like longitudinal loads, many transverse loads are influenced by the environment and are therefore probabilistic. Unfortunately, it is even more difficult to devise a rational probabilistic procedure for transverse strength analysis than it is for longitudinal strength. Consequently, it is necessary to use deterministic as well as static methods for the derivation of design loads and, as will be seen later (Chapter 3), some of these are somewhat arbitrary.

Cyclic Effects of Ship Life

10 Cyclic loads due to waves or other effects can cause fatigue damage to the structure over a period of time. It is therefore always necessary to define the expected life of a structure which is to be subjected to cyclic loading, and this applies especially to the hull of a ship. For convenience the life of a ship is often defined by a number of wave encounters, based on the life of the ship in years, the expected proportion of time spent at sea and the mean period of a wave (usually between 7 and 8 seconds). For example, a ship with a 25 year design life, 30% of which is likely to be at sea with a mean wave encounter period of 8 seconds, will suffer approximately 3×10^7 wave encounters. This number of wave encounters has been used in the recent past for the design of RN warships. However, current developments are such that both the lifetime in years and proportion of time spent at sea are increasing, and the number of wave encounters which it is desirable to use for design may be significantly greater.

11 A lifetime definition in wave encounters may also be used statistically in the definition of design load, for example, by mathematical modelling or by extrapolating from strain measurements at sea, the load with a given probability of exceedance in the specified number of wave encounters can be estimated. This aspect is discussed in detail in Chapter 7.

Combined Loads

12 Since some transverse and longitudinal loads can occur simultaneously it is necessary to remember that in certain circumstances transverse loads can reduce longitudinal strength and vice versa. In theory, these reductions in strength may be brought about in several ways, because transverse loading involves not only bending in both the longitudinal and transverse directions, but also transverse membrane effects in the plating. Fortunately it has been found by both theory and experiment that most of the possible interactions are of little significance in typical warship structure as discussed by Sadden (1976). In fact, for surface warships of conventional configuration, and with no unusual structural arrangements, it is only necessary to make explicit allowance for the interactions between longitudinal and transverse loads when designing the bottom and tank tops. However, the possibility of small interactions occurring in other parts of the structure must be remembered when selecting load factors. Furthermore, the possibility of more significant interactions between different but simultaneous loads must always be assessed if a structure is in any way unusual.

Concentrated Loads

13 Concentrated loads are imposed on the structure of ships by heavy items of equipment, and in warships by the operation of their weapon systems. Concentrated loads have a static component together with a superimposed cyclic component resulting from the inertial effects of ship motion. Weapon loads are usually impulsive, for example gun recoil, but may also combine the effects of heavy loads, for example aircraft landing and aircraft parked.

Explosive Loads

14 During the design of warships, due regard must be paid to explosive attack. If a charge is large enough and suitably positioned it can cause extensive distortion of the plating and stiffening associated with large amplitudes and velocities of motion. For underwater attack the amplitudes of overall hull vibration may also be sufficient to break the ship's back. These effects and the means of reducing them in the design of the structure are discussed in Chapter 15.

Classification of Structure and Stresses

15 The following classification into primary, secondary and tertiary elements shown in *Figure 2.2* seems to have originated in Germany with Lienau (1913) in the early part of this century. The primary structure is what has already been discussed, that it the complete hull as a beam, including the shell, principal decks, main transverse bulkheads (required for maintenance of the form of the hull) and possibly superstructure depending on its effectiveness. Secondary structure consists of stiffened panels and grillages bounded by decks, bulkheads and the shell; tertiary structure may be panels of plate bounded by stiffeners or elements of stiffeners themselves. The simplification that results from such a breakdown is the analysis of each component independently of others, although cross coupling effects are thereby neglected and care must be taken with boundary and support conditions. The utility of the distinctions is now less than it used to be as modern computing techniques allow all the structure to be analysed at once. However, it is still valuable during the synthesis phase when individual elements of the structure need to be sized and assembled into a composite whole.

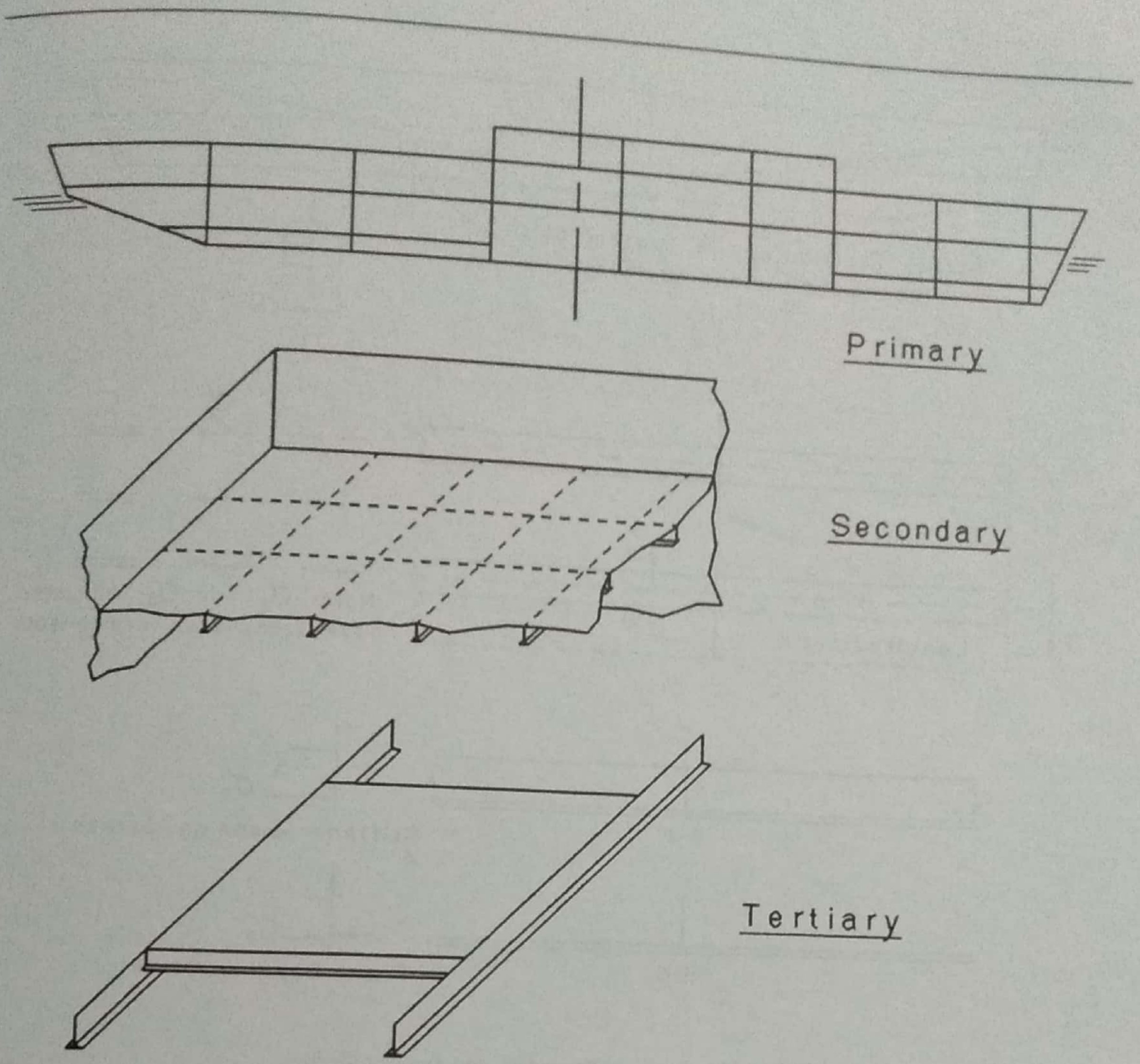

Figure 2.2 Primary, Secondary and Tertiary Structure

16 Stresses can be classified in a similar way to the structure in which the stresses are occurring and to the loads which cause the stress as illustrated in *Figure 2.3*.

σ_1 *primary* - stresses due to bending, shear and torsion in the main hull girder.

σ_2 *secondary* - stresses in a stiffened grillage due to bending and membrane effects.

σ_3 *tertiary* - membrane stresses in panels between stiffeners.

Note that in general each element of structure may contain stresses of all types.

17 The utility of these definitions is similar to that for structure, that is, it is frequently convenient to calculate stresses at each level separately and to superimpose them to obtain a complete solution. Again the greatest advantage will be seen at the initial design stage when the

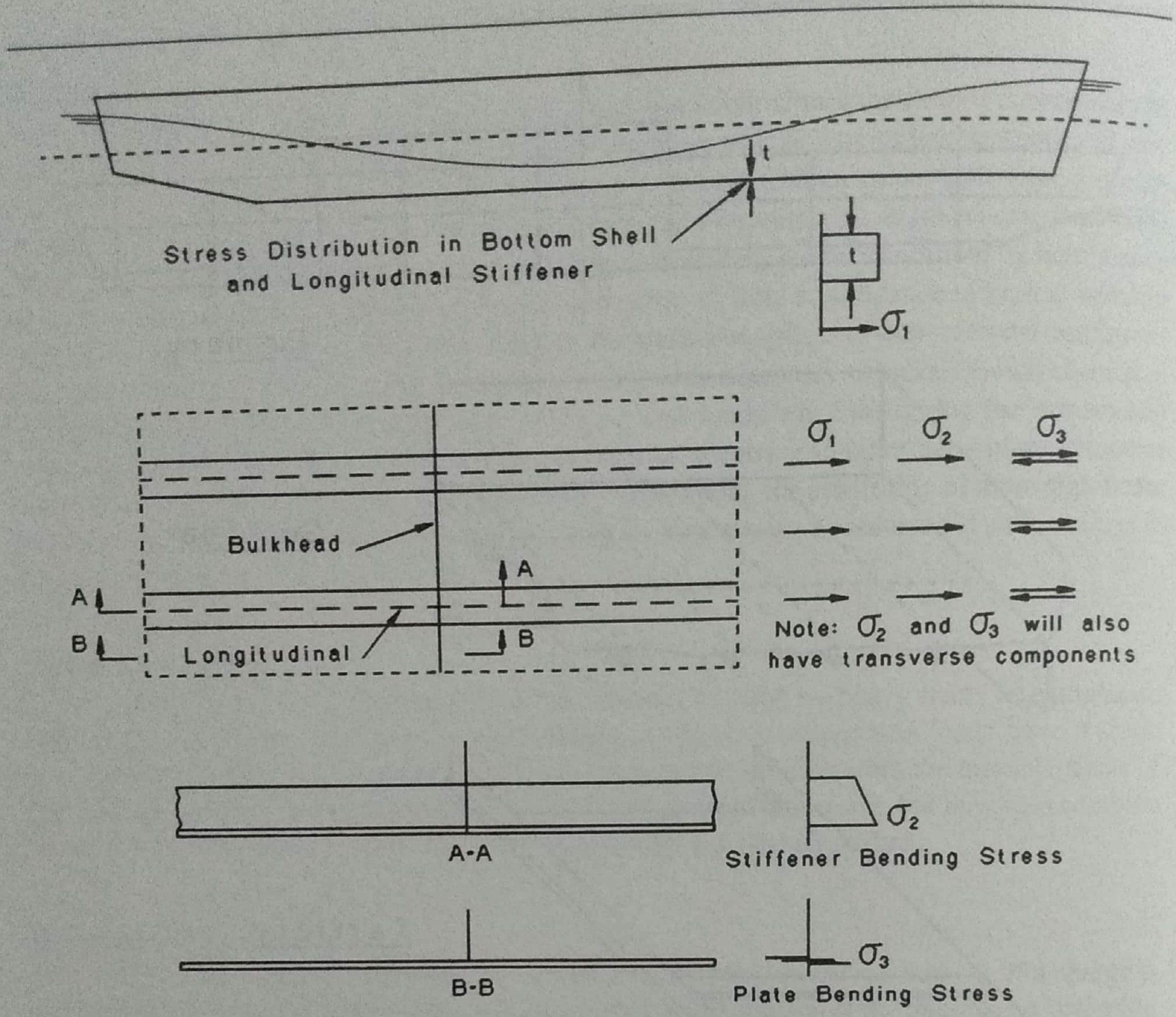

Figure 2.3 Primary, Secondary and Tertiary Stresses

calculations are in the main being done by hand. Later, when the majority of the work is done by the computer, the definitions will not be apparent and indeed could be misleading due to the loss of interaction effects between the different levels.

Load Transmission

18 The *primary - secondary - tertiary* stress breakdown can be considered in reverse in the synthesis of structures when considering load transmission. Lateral loads on long plates can be visualised as being transferred mainly to longitudinal stiffeners along the panel long edges, thus defining the panel boundary conditions and response. The load in the longitudinal stiffeners is transferred to the transverse stiffeners, again defining boundary conditions and response of the longitudinals and associated plating. The load is thence transferred to the grillage boundary which is usually very stiff in the plane of the load, for example deck loads being passed into bulkheads. The extent to which a structure can actually be broken down in this way depends strongly on the relative stiffness of adjacent components and is most reliable for large differences in stiffness such as light longitudinals and heavy beams.

19 A corollary of the concept of load transmission is that there must always be structure to which load can be transferred. Unsupported deck or bulkhead edges must always be avoided, as should unsupported stiffener ends. Never, for example, end a stiffener in the middle of a plate panel as it will not be possible for the stiffener to pass its load onwards adequately and the plate will be locally over-stressed resulting in fatigue cracking. Similarly, it is vitally important that all structure bearing very high loads, such as the ends of superstructures or masts, are well integrated into the primary structure of the ship so that the loads are taken by stiff structure in plane. Lack of structural continuity is one of the principal reasons for severe structural failures, and discontinuities such as blocks of superstructure frequently become part of the design at a very early stage before the designer has begun to think seriously about the structure. Later in the design process it can be extremely difficult to change the layout to provide adequate continuity, so it is essential for the structural designer to ensure good continuity from the beginning.

Effective Breadth and Width

20 The question of effectiveness of structure has already been mentioned in paragraph 2. At a secondary level the concepts of effective breadth and width need to be understood. Consider, for instance, part of a stiffened panel shown in *Figure 2.4(a)*. As the stiffeners deflect under the loading shown, the load is transferred into the plate by shear action with the result that plate deflects out of plane progressively less than the stiffener and the 'plane sections remain plane' assumption of simple bending theory is strictly invalid. The effect is called shear lag and leads to an in-plane stress distribution illustrated in *Figure 2.4(b)*. Not all the plate therefore bends with the stiffener and an effective *breadth* with a constant stress level is defined as in *Figure 2.4(c)*

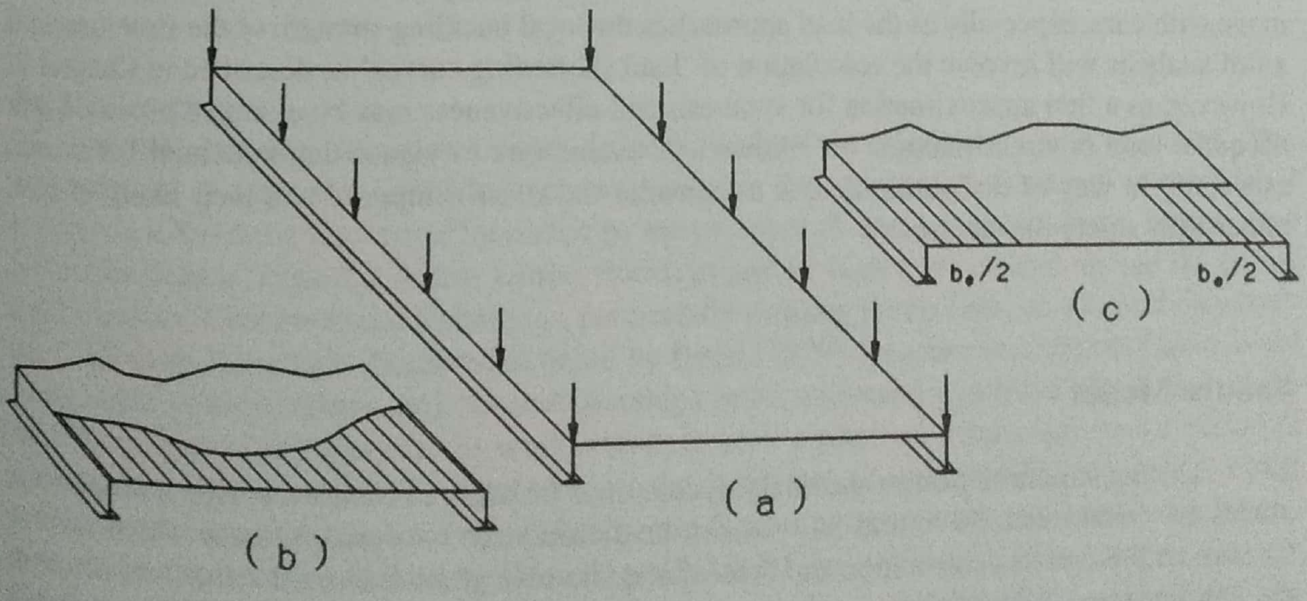

Figure 2.4 Effective Breadth

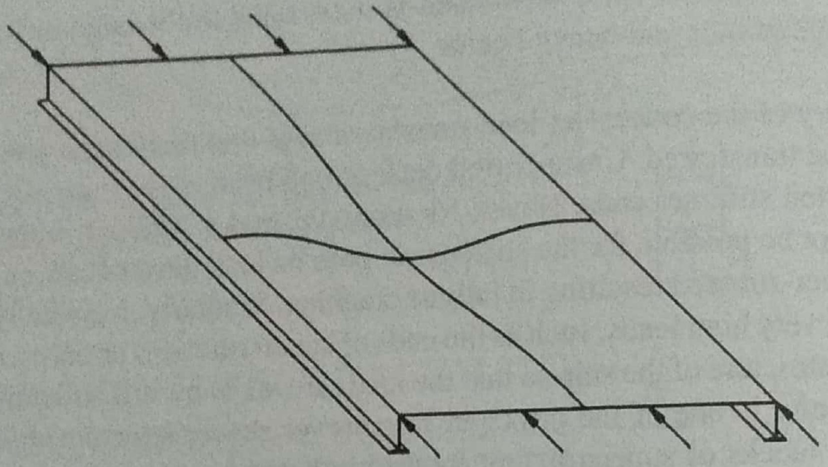

Figure 2.5 Effective Width

which is used to calculate the bending stiffness of the plate-stiffener combination. The value of b_e will be a function of panel aspect ratio and thickness, as well as load distribution, panel flatness and residual stresses. The remainder of the plate, beyond the effective breadth, is assumed to have zero stress.

21 A parallel case occurs for in-plane loading, shown in *Figure 2.5*. Here the non-uniform stress distribution does not arise from shear lag but from lack of homogeneity. A similar assumption is made as for that shown in Figure 2.4(c) but is here known as effective *width* and is a function of flatness and residual stress, and of load intensity in relation to the elasto-plastic buckling strength of the plate.

22 For most ship structures, for *primary* stresses, that is hull bending as a beam, all plating is usually taken effective when it is in tension, that is upper deck in hogging and keel in sagging. In compression, because of the problem of effective width, assumptions of effectiveness have to be made with care, especially as the load approaches the local buckling strength of the structure, and a full analysis will involve the calculation of 'load shortening curves' as described in Chapter 7. However, as a first approximation for synthesis full effectiveness may be assumed provided that adequate load or stress margins are allowed. A useful way of visualising structural behaviour, especially in way of discontinuities, is to consider the *strains* imposed and their likely effects, rather than solely the stresses.

Failure Modes

23 During structural design and analysis care must be taken to ensure that all possible failure modes are considered. Structural failures can be divided into two groups, those which involve fracture without gross deformation and those that do involve gross deformation but not fracture in the first instance. Each of these groups can be further subdivided as shown in *Table 2.1* and as follows:

TABLE 2.1
Structural Failure Modes

Loads → Failure ↓	Tensile	Shear	Compressive	Cyclic
		← - - - - - - - - - - - - - - - - In-Plane Loading - - - - - - - - - - - →		
Yielding	Out of Plane Bending		Out of Plane Bending	■
		← - - - - - - - - In-Plane Loading - - - →		
Elastic/Plastic Buckling	■		Lateral Loads (Stiffener Tripping)	■
Fatigue	■	■	■	Loads mainly in Tensile Range (Residual Stress, Corrosion Fatigue)
	← - - - - - - - Impact, Explosion - - - - →			
Brittle Fracture	(Stress Corrosion)		■	■

Fatigue

24 Because the majority of the loads imposed on ships are cyclic as mentioned in paragraph 10, the possibility of fatigue failures must never be forgotten. Indeed, most structural failures that occur in service are the result of fatigue damage. Generally, however, fatigue effects do not dominate the main design process as they are governed by design of detail which is not usually considered until the final construction drawings are being produced. It is, therefore, of paramount importance that good detail specifications are written which make it quite clear how stress concentrations are to be avoided or at least minimised, and that these specifications are made mandatory contractual requirements. Design against fatigue is discussed in detail in Chapter 13.

Brittle Fracture

25 Brittle fracture has caused many failures, both of merchant ships and warships. The susceptibility of a structure to brittle fracture is crucially dependent on the material from which it is constructed, but the risk is also increased by the presence of stress concentrations, notches and notch like defects, exposure to low temperatures, impact or high rates of loading and the use of thick material. Constructional techniques, particularly welding procedures, also have their part to play. All these factors are discussed in detail by Boyd (1970). Because it is impossible to avoid some stress concentrations, and because warships must withstand explosive attack and at the same time operate anywhere in the world where there is a political needs, and over a period of time during which operational and political requirements may change significantly, it is essential to select hull materials which are resistant to brittle failure, even under Arctic conditions. It must be noted at the outset that **mild steel**, such as BS4360 Grade 43A or a Classification Society Grade A, does not have any toughness requirement specified, and therefore, while it may be acceptable for merchant vessels operating under prescribed benign conditions, it will not be acceptable for warship hull material. It has been demonstrated by Sumpter et al (1989) that during operations off Iceland in the so-called Cod Wars in the 1970s and in subsequent laboratory testing there is no practical thickness of fabricated mild steel below which brittle fracture may not be exhibited. Consequently, steels with a specified toughness must be used for the hulls of ships likely at any time in their lives to operate in cold conditions and especially if high rates of loading are possible. Corlett et al (1988) have shown that even collision with an ice flow or impact from a heavy sea is sufficient to precipitate brittle fracture under certain conditions, which in their case was exacerbated by a steep temperature gradient through the steel.

Plastic Collapse

26 This will take place when yielding occurs in sufficiently large volumes of material such that very small increases in load cause large increases in deflection. It may be caused by loads of any type and in any direction but the most important in ship structures are lateral load and in-plane load.

27 Plastic collapse under **lateral loading** involves the formation of sufficient plastic hinges to form a mechanism. It is not precipitated by yielding at a single point. Unfortunately, plastic collapse load prediction methods which are readily applicable during design exist only for relatively simple structures. In contrast, many analytical techniques are available to predict stresses in the elastic regime. Consequently, most of the recommendations for estimation of strength under lateral loading are intended to prevent yield occurring under severe but not extreme loads, relying on the usually substantial reserves of strength in a ductile material to avoid total collapse under the rare extreme load. This philosophy also ensures that under most conditions deflections will not be excessive. However, under emergency loads after which repair might be expected in any case, plastic design methods may be more appropriate and their use should be considered.

28 Plastic collapse takes place under **in-plane loads** when average direct and shear stresses combined reach an intensity which corresponds to yield. In practice this particular mode of failure is only important in special circumstances, because under tensile loads permissible stresses are often limited by the need to prevent fatigue cracking at the many discontinuities and stress concentrations which are inevitable in ships. More importantly, in an efficiently designed structure a combination of yielding and elastic buckling will occur before pure yield and this is explained in paragraph 30 below.

Elastic Buckling

29 This can take many different forms. It may be confined to the plating or to the webs or the flanges of stiffeners; it may occur by tripping or by flexure of one set of stiffeners between an orthogonal set; or it may involve an entire grillage. Care must therefore be taken during design to ensure that all possible buckling modes are taken account of, noting that most forms of buckling will result sooner or later in complete collapse of the structure. (There are a few forms of buckling which are followed by a strengthening mechanism giving some reserve of strength, for example shear buckling leading to a membrane tension field, but these can rarely be used quantitatively in design.) Furthermore, the initial deformations and residual stresses that occur during fabrication will almost always lead to some loss of buckling strength and must be taken into account when estimating critical buckling stresses. Finally, remember that stiffener tripping and some other modes of local buckling can be caused by lateral loads as well as by in-plane loads.

Elasto-Plastic Buckling

30 In efficient structures elastic buckling loads are usually higher than loads to first yield of the material and therefore collapse will involve a combination of buckling and yield failure known as elasto-plastic buckling. Because of the non-linear nature of the phenomenon and its dependence on factors such as initial deformation and welding residual stress, the mode shape and stress at failure can only be predicted using numerical methods. These methods are now available and adequately validated for ship design, for example Creswell and Dow (1986). In the particular case of in-plane loads on rectangular plates the results of numerical analyses can be reduced to a few graphical representations, for example Smith et al (1988), and the use of these in design is discussed in Chapter 7. More traditional methods are available, mainly based on the use of a tangent modulus derived from the part of an estimated failure curve lying between the elastic and plastic failure zones. These methods have their uses particularly during the early synthesis stages for quick checks on adequacy of scantlings.

Excessive Deflections

31 There are often specific limitations on allowable deflections in way of weapons or machinery. Design methods to meet these requirements are mostly straightforward as they are by definition linear-elastic. However, care must be taken to allow for the effects of residual stresses which may cause greater than expected deflections on first application of the load. Generally in design, even where there are no specific deformation limits, it is not good practice to accept large elastic deflections as there may then be unexpected interference with the performance of equipments nearby. Additionally there may be specific deflection limitations between weapons and their associated sensors. This will be of particular importance if materials of lower stiffness such as fibre reinforced plastic (FRP) are used.

Vibration

32 As already mentioned, the majority of significant loads on a ship's hull are cyclic but at a sufficiently low frequency that they can be treated as static. However, there are particular locations on a ship where the vibration response may be important, such as in way of weapons, sensors and machinery, and in the stern region, and checks on resonant frequencies will need to be made in these areas. These checks will be even more important if unconventional materials or methods of construction are employed. The checks should ensure that resonant frequencies, especially of masts, seatings and other equipment supports, are not too close to propeller shaft and blade rate frequencies at full power, rotational frequencies of auxiliary machinery and the natural frequencies of shock and vibration mountings. It is possible, using predictive techniques, to make estimates of hull resonant frequencies and mode shapes at a stage in the design when it is still possible to influence them and perhaps to tailor the hull response to match the requirements of equipment sensitivities and layout; these techniques will be discussed in Chapter 6, and vibration problems in design are covered in Chapter 14.